Chapter 13

Hydrodynamic Modeling for the Lake Michigan Mass Balance Project[1]

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Abstract

A three-dimensional primitive equation numerical ocean model, the Princeton model, was applied to Lake Michigan in support of the EPA Lake Michigan Mass Balance Project (LMMBP). The model has 13 vertical levels and uniform horizontal grid size of 5 km. For the LMMBP, the model will be driven with observed meteorological conditions for the study years of 1994 and 1995. As a model test we chose a case with strong northerly wind in August 1955 to compare Kelvin waves in the model with observations presented by Mortimer (1963). Therefore, the model was driven with an impulsive wind stress imitating the passage of the weather system. Under the strong wind forcing, the thermocline breaks the surface along the eastern shore, and a thermal front appears. After the wind cessation, the edges of this thermal front propagate cyclonically around the lake in the form of a coastally trapped Kelvin wave. Although initially the strong upwelling front in the model compared favorably with observations, the speed of the Kelvin wave in the model was less than the speed obtained from observations.

13.1 Introduction

An advanced three-dimensional numerical ocean model, the Princeton model of Blumberg and Mellor [1], was applied to Lake Michigan in support of the U.S. EPA Lake Michigan Mass Balance Project (LMMBP). The model has a terrain-following (sigma) vertical coordinate and the Mellor–Yamada turbulence closure scheme. The model has 13 vertical levels and uniform horizontal grid size of 5 km. The bathymetry was modified so that

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the relative difference in depth between any two adjacent grids was not larger than 0.5 i order not to exceed the hydrostatic consistency criterion for σ-coordinates. The model us barotropic and baroclinic time steps of 30 and 900 seconds, respectively. For the LMMBI the model will be driven with observed meteorological conditions for the study years 199 and 1995. In this paper we present results of one test case, describing the internal wav response of the lake to a wind forcing.

13.2 The Kelvin wave case

Following major wind events, coastally trapped internal Kelvin waves appear in the nearshore hydrodynamics of large lakes in summer. Because of their long periods (up to several weeks), they have a profound influence on the intraseasonal variations of coastal thermal structure and currents, especially coastal jets. The accurate simulation of these characteristics is necessary for the particle transport model used in the LMMBP.

For the model test we have chosen the 9 August 1955 case, with strong northerly winds, to compare upwelling and Kelvin waves in the model with observations given by Mortimer [2]. Before the storm, the thermocline was located between 10 and 20m, but after 1.5 days of strong winds it had risen to the surface and shifted up to 15 km offshore, as was determined by temperature observations taken two days after the storm. The following week was characterized by the absence of significant wind events, and so the thermocline relaxed with the warm front moving northward along the eastern shore. The frontal speed was approximately 0.45 ms^{-1}.

To initialize the models it is necessary to know the three-dimensional thermal structure and currents in the lake. To deal with this problem, we can postulate that during major wind events, wind-generated currents are usually dominant over preexisting ones. Therefore, the no-motion condition was assumed for the initial velocity field. To obtain the initial thermal structure, we used observations from several stations made soon after the storm, because the closest survey before the storm was made on 29 June.

13.3 Results

The model was driven with an impulsive wind stress imitating the passage of the weather system on 9 August 1955. After one day of wind forcing, the model produced strong upwelling that compared favorably with observations. Subsequently this upwelling relaxed, and the model showed the propagation of the warm front northward along the eastern shore. Time series plots of temperature in Figure 13.1 show that the initially sharp thermal front diffused faster in the model than in the observations. The warm front propagation speed, determined by the time between the sharp temperature increases at 13 m depth at Benton Harbor and Muskegon, is approximately 0.25 ms^{-1}. There could be several reasons why the model underestimated the frontal speed, including physical and numerical diffusion, uncertainty in the initialization of the thermal structure, and surface heat flux not accounted for in the model.

13.4 Conclusions

The Princeton model was tested against the August 1955 upwelling case [2] in Lake Michigan. Strong upwelling iu the model compared favorably with observations. The model is also able to simulate the propagation of the Kelvin wave around the lake. However, when compared with observations, the initially sharp front diffuses faster in the model and the predicted wave speed is less than that observed.

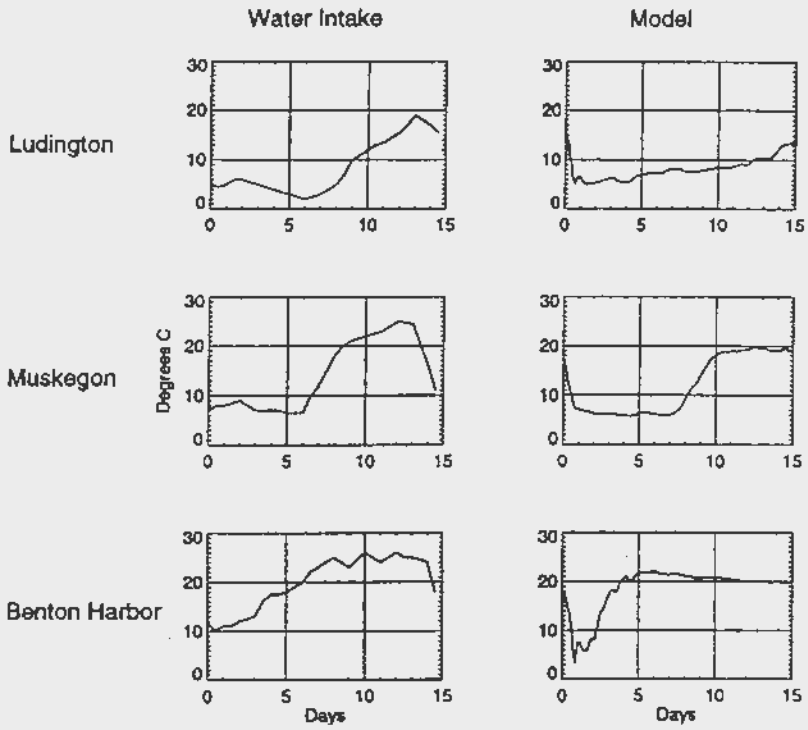

FIG. 13.1. *Time series of 13m temperature observed at Benton Harbor, Muskegon, and Ludington [2], and calculated by the model described here.*

References

[1] A.F. Blumberg, and G.L. Mellor, A description of a three-dimensional coastal ocean circulation model, *Three-dimensional Coastal Ocean Models, Coastal and Estuarine Sciences*, 4 (1987), pp. 1-16, N.S. Heaps, ed., Amer. Geophys. Union, Washington, DC.

[2] C.H. Mortimer, Frontiers in physical limnology with particular reference to long waves in rotating basins, *Great Lakes Res. Div. Publ.* (University of Michigan), 10 (1963), pp. 9-42.

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